Biochar: The science behind the hype

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USDA/ARS – St. Paul, MN

April 5, 2013 – Seminar at Illinois Biochar Group Meeting

Biochar

- What is it ?

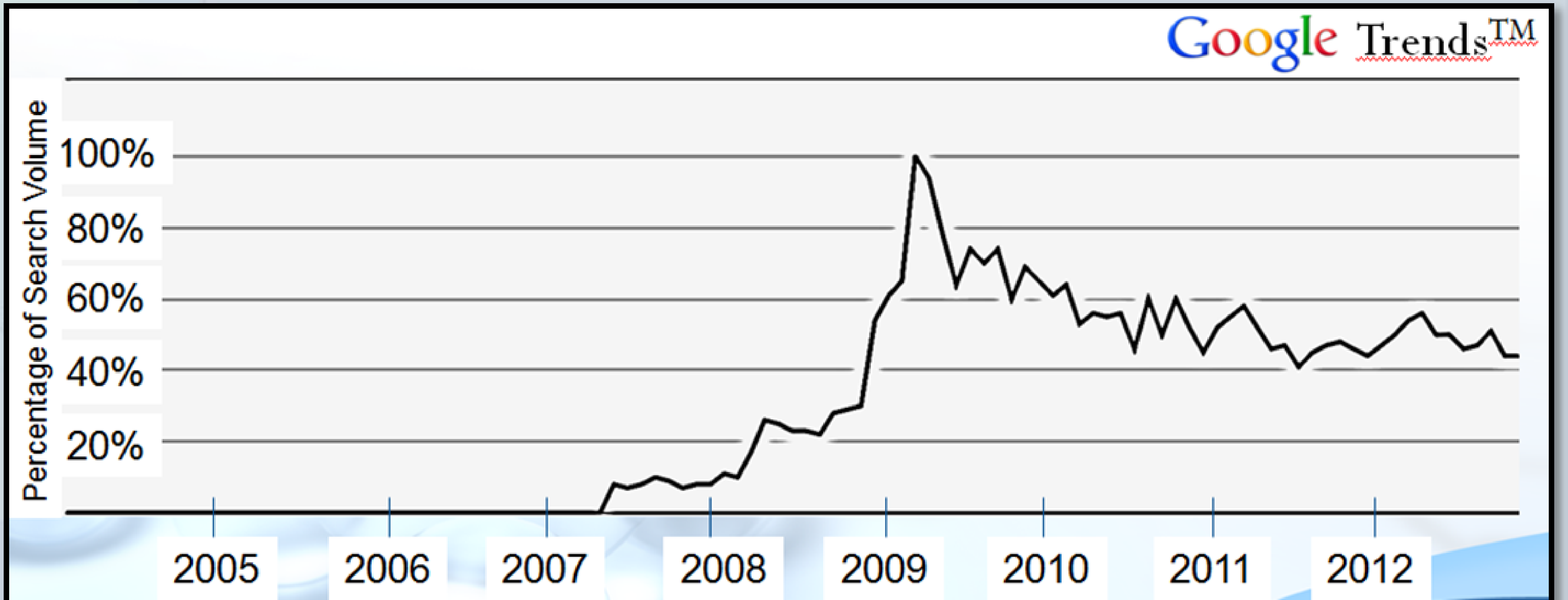



Biochar

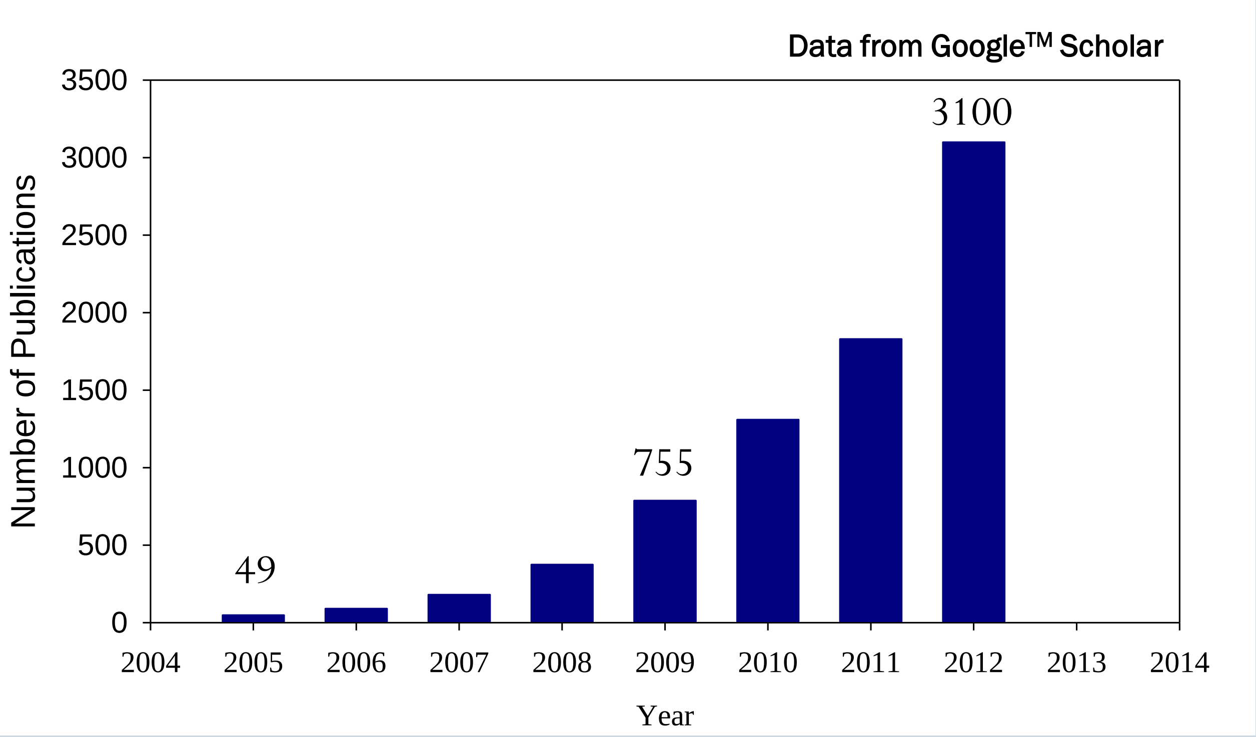
- “**Biochar**” first used in 1988

Biochar

- "**Biochar**" first used in 1988
- Looking at Google Trends™



“Biochar” Manuscripts: 2005-2012



- ➢ Increasing number of scientific outputs

Defining Biochar

• *Biochar is Black Carbon*

Range of solid residual products resulting from the chemical and/or thermal conversion of any carbon containing material (e.g., fossil fuels and biomass) (Jones et al., 1997)

Black Carbon

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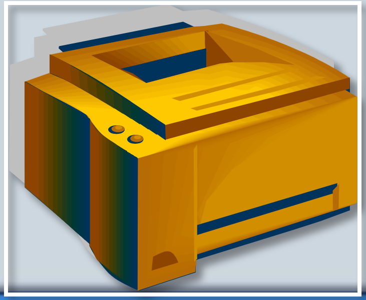
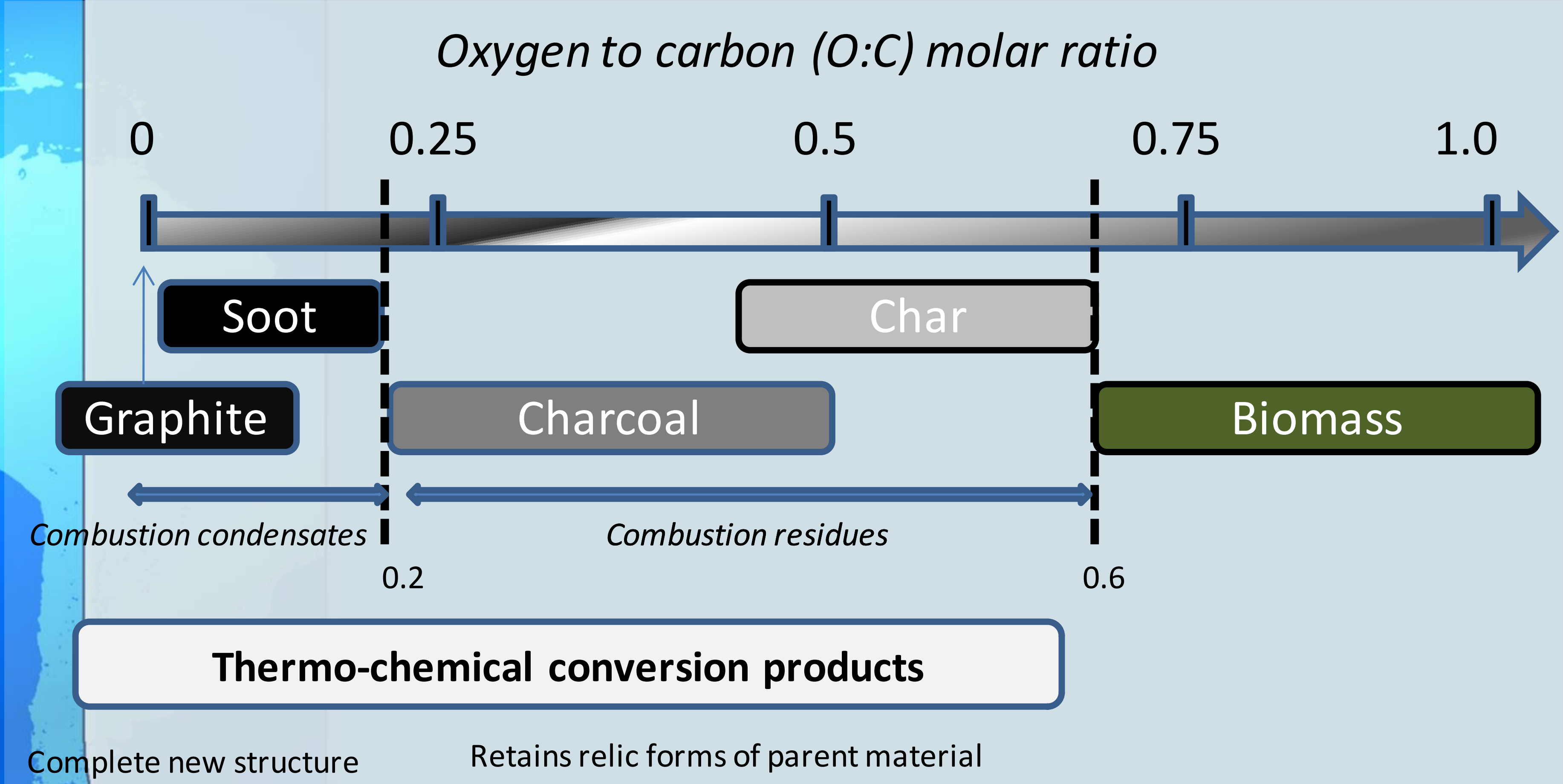


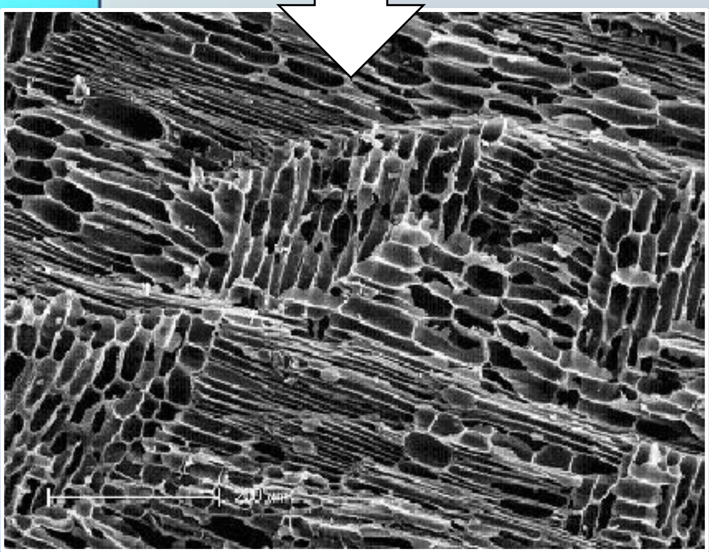
Biochar: Black Carbon Continuum

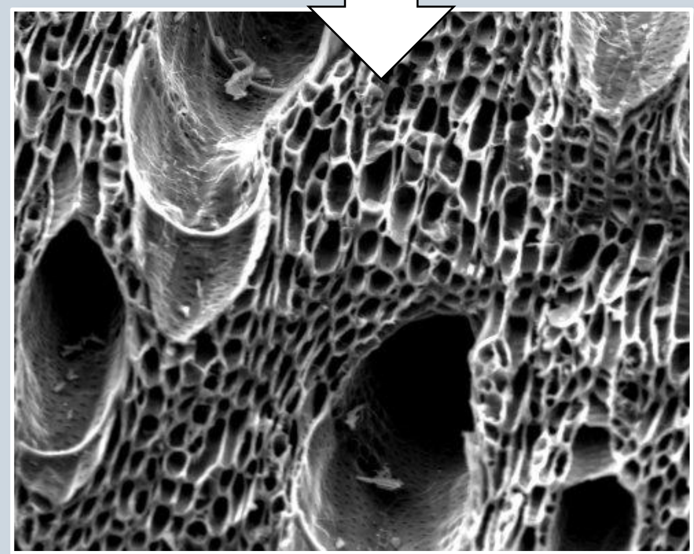


Adapted from Hedges et al., 2000; Elmquist et al., 2006; Spokas, 2010

Biochar: Structure

Pyrolysis (biochar)



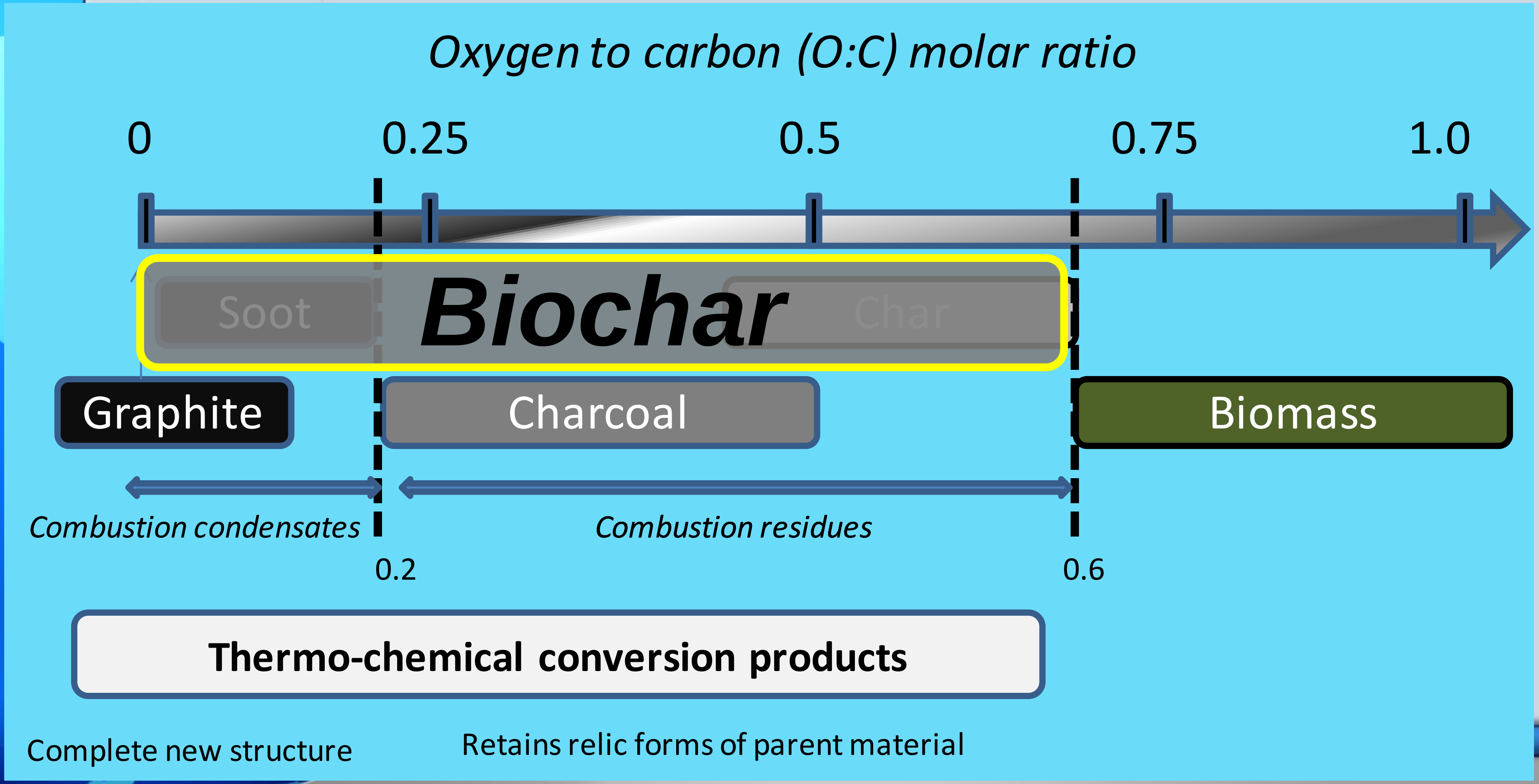


- Biochar : Majority still show relic structures in the biochar

Biochar is Black Carbon

Biochar – Spans across <u>multiple divisions</u> in the Black C Continuum

However, *<u>biochar is NOT a new division or material</u>…*

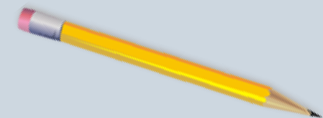


Adapted from Hedges et al., 2000; Elmquist et al., 2006; Spokas, 2010

Black Carbon Use

- We have used black carbon in the past….and currently

Cave Drawings
(>10,000 to 30,000 BC)

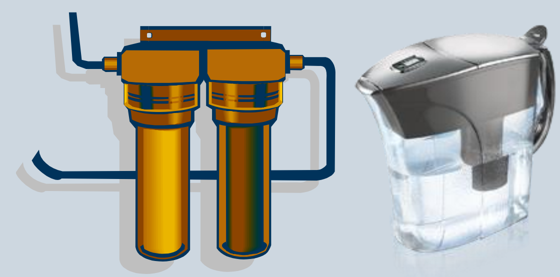


Pencils

Used as fuel
(3000-4000 BC)

Charcoal production
(15th century)

Water filtration (2000 BC)



Activated charcoal filtration

Biochar: New purpose not a new material

➢ What is new?

The use (or purpose) for the creation of black carbon

Atmospheric C sequestration

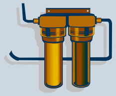
Dates to mid-1980’s and early 1990’s

(Goldberg 1985; Kuhlbusch and Crutzen, 1995)

Cave Drawings
(>10,000 to 30,000 BC)

Used as fuel
(3000-4000 BC)

Water filtration
(2000 BC)



Charcoal production
(15th century)

Climate Change
Mitigation
(1980’s)

Biochar Definition

Biochar is black carbon that is made for the purpose of carbon sequestration

Biomass Materials

Pyrolysis

Easily degradable
(0-5 yrs)

Recalcitrant carbon form
(black carbon)
(>50 to 1,000,000 yrs?)

Biochar Differences

Similar to baking…
The same recipe –
might not taste the same
cook to cook

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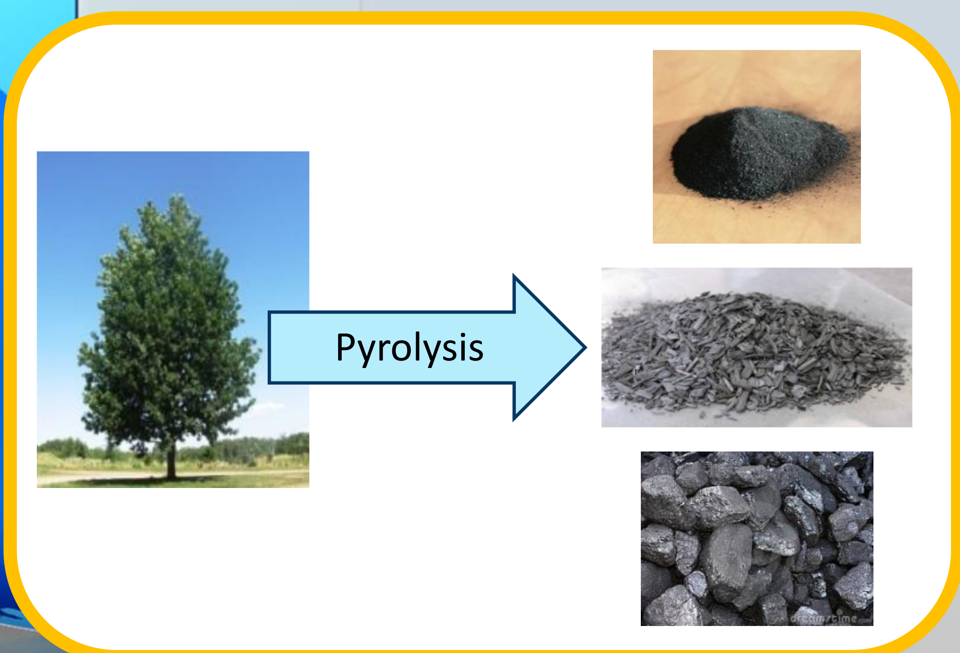


Even though same conditions –

Pyrolysis can result in different biochar chemistries

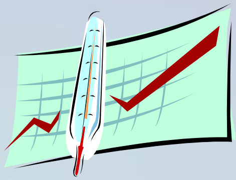
"Not all biochars are equal"

Biochar Production

Several different methods : Pyrolysis

- Current emphasis and reporting in literature:
  - Feedstock
  - Production Temperature
  - Reaction Time

Other Factors



- Rate of heating/cooling can be more important than pyrolysis temperature

(Kashiwaya and Ishii, 1991; Sahu et al., 1988)

Increase number of “active sites”

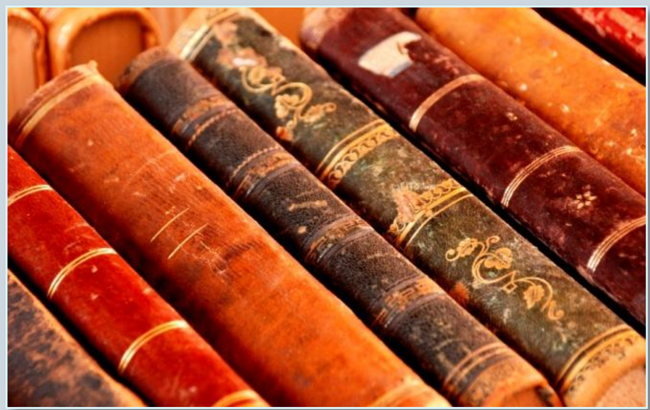
- Feedstock Properties:
  - Moisture content
  - Particle size
  - Inorganic constituents

- Cooling Conditions:
  - Inert gas or reacting with air/water
  - Exposure to weather conditions

BIOCHAR RESEARCH HISTORY

"Those who don't know history are destined to repeat it."

-E. Burke



Biochar Research History

1800 | 1900 | 2000

Gunpowder Years (1810 – 1920’s)

<u>Major emphasis of scientific efforts</u>

•Munroe (1885)

"*Gunpowder is such a nervous and sensitive spirit, that in almost every process of manufacture; it changes under our hands as the weather changes.*“

Overall gunpowder reaction:

$$\mathbf{6\ KNO_3 + \underbrace{\boxed{C_7H_4O}}_{\text{Charcoal}} \longrightarrow 3\ K_2CO_3 + CO_2 + 6\ CO + 2\ H_2O + 2\ N_2}$$

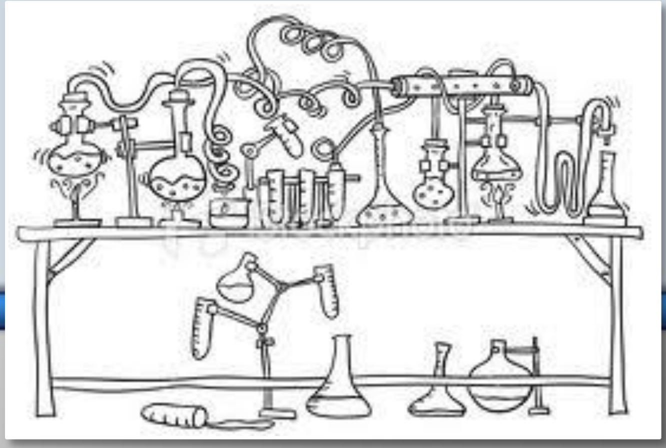
Biochar Research History

1800 → 1900 → 2000

<u>1900's:</u>

- Discovery of charcoal activation
  - > Steam activation (Ostreijko, 1900)
  - > Chemical activation (Bayer, 1915)

Took over 4000 years from discovery of sorption processes by charcoal before optimization.

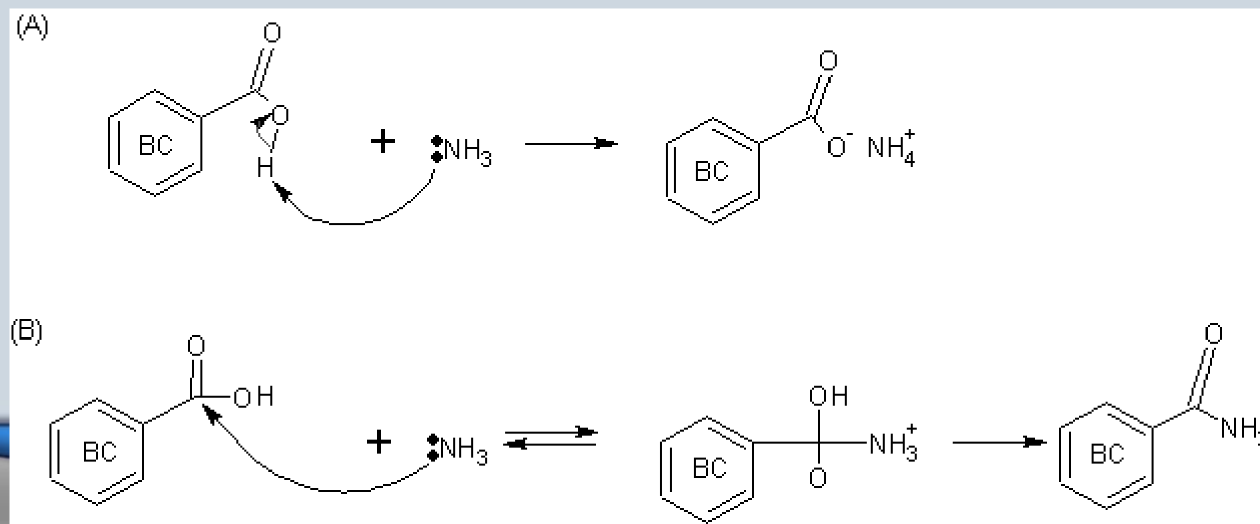


Biochar Research History

1800 | 1900 | 2000

1920-1950's

- Focus on use of charcoal in analytical methodology
  - -Observed disappearance of N-forms (interference)
    - -[e.g., Harper 1924; Burrell and Phillips 1925; Gibson and Nutman 1960; Scholl et al. 1974]



•Biochar Research History

1800 → 1900 → 2000

1960's→

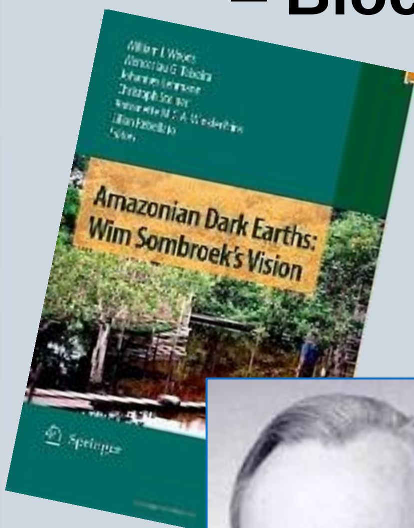
- **Actions of charcoal linked to sorptive properties**
  - **Turner (1955)**
    - Positive yield improvements due to sorption of plant "putrids"
  - **Weatherhead et al. (1978)**
    - Plant chemical inhibitors (auxin and cytokinin) sorbed by charcoal
  - **Hitz et al. (1953)**
    - Used activated charcoal for strawberry seedling protection from herbicides

Biochar Research History

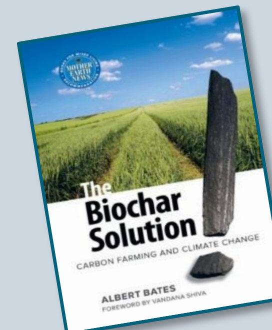
1800 | 1900 | 2000

1985-Current

– Biochar Renaissance



Wim Sombroek



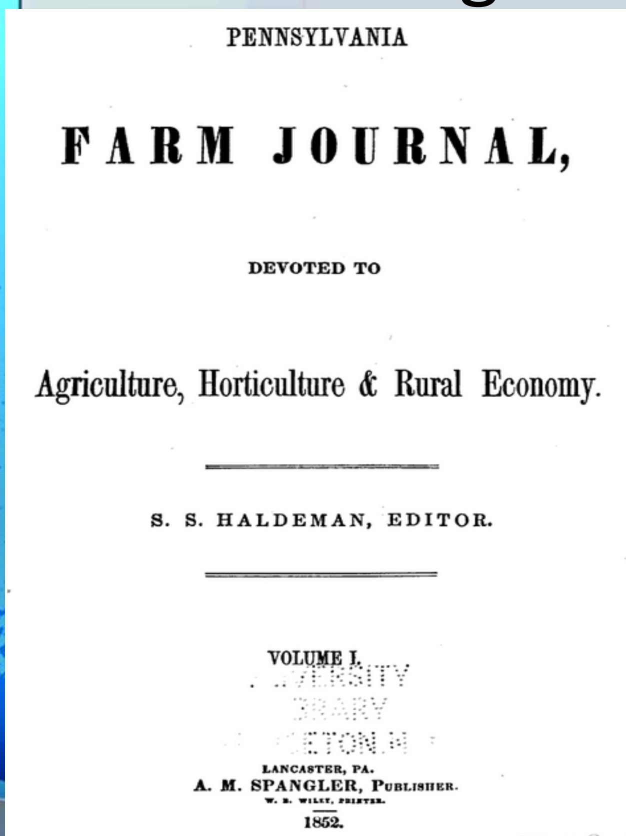
BIOCHAR SOIL APPLICATION

"The best manures for onions are said to be sea weed and charcoal dust."

Fressendeen (1834) – American Farmer Journal

Biochar Soil Amendments

"The use of charcoal (*biochar*) as a fertilizer is not a new thing, but only in the last few years that agriculturists have taken notice of it."



PENNSYLVANIA

FARM JOURNAL,

DEVOTED TO

Agriculture, Horticulture & Rural Economy.

S. S. HALDEMAN, EDITOR.

VOLUME I.

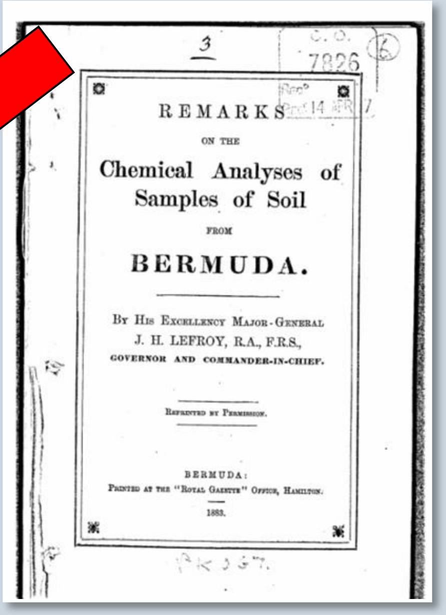
LANCASTER, PA.
A. M. SPANGLER, PUBLISHER.
W. B. WILEY, PRINTER.
1852.

- ***Editorial in the 1st volume of the Pennsylvania Farm Journal (1852)***

Soil Application… Long History

- Biochar applications date back to the beginning of modern science [1800's]:

Ashes (see also *Potash*) "constitute an important class of manures, differing, however, in their effects according to the substance which has undergone the process of burning, and the manner in which the process has been accomplished. The ashes of all vegetable substances consist principally of those substances which plants require, as charcoal, lime, phosphoric acid, and alkaline salts. Of these charcoal or carbon is the most valuable, and hence to secure it in the greatest quantity the process of burning should be carried on as slowly as possible, and this is best effected by covering up the mass while burning and admitting no more air than just sufficient to keep up a smouldering fire. The ashes of all vegetables contain almost the same constituent parts, and are found useful in all soils and to the majority of crops. They should always be applied when newly burned, as they lose much of their value by keeping even although kept under cover. A medium quantity of ashes may be taken as 1 lb. weight to the square yard."* Coal ashes finely screened are also useful as manure, but less so than wood ashes. The ashes of sea weed, known in England as kelp, contain carbonate of soda and salts of potash, and are much used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REMARKS

ON THE

Chemical Analyses of Samples of Soil

FROM

BERMUDA.

By His Excellency Major-General J. H. LEFROY, R.A., F.R.S., GOVERNOR AND COMMANDER-IN-CHIEF.

Reprinted by Permission.

BERMUDA:

Printed at the "Royal Gazette" Office, Hamilton.

1883.

(John Henry LeFroy, 1883)

Quote is from a 1833 report

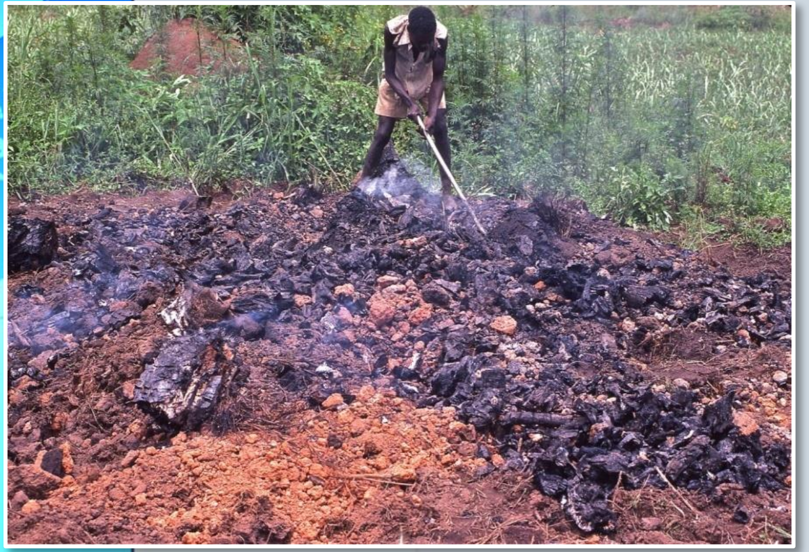
Application rate ≈5000 lb/ac (5500 kg/ha)

Past Charcoal Uses

- Improving yields (peat charcoal)
  - Oats – 2-fold increases reported
  - Grasses - improved growth & color
  - Potatoes – Improved yield 2-fold
- Increasing soil temperature
  - Earlier crop germination/emergence (1730)
- Charcoal mixed with manures
  - "Improved fertilization action" (1834)
- Reducing plant pathogens
  - Particularly for potatoes, peach trees

  "One handful of charcoal with each seed" (1834)
- Patents in the 1850's for "Antiseptic fertilizer"

The Biochar Renaissance



- The assumed target for biochar has been soil

<u>Why?</u>

•The Biochar Renaissance

- The assumed target for biochar has been soil

Why?

→Focus has been on "creating" *Terra Preta* soils

- Observations of increased soil fertility and productivity

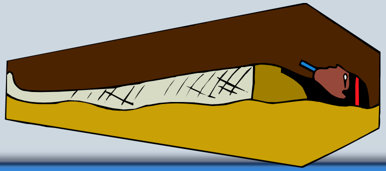
  - Postulated from 'slash and burn' historic charcoal additions

  - Other possibilities ?

Biochar: Soil Application History

However, on the other side:

- <u>Wood distillation plants</u> *1800 - 1950's*
  - Wood pyrolysis – source of chemicals and energy prior to petroleum (fossil fuels)
  - 1920 – approximately 100 plants (11,000 tons wood/day)
  - Some historic plants on US-EPA Superfund site list
- <u>Other charcoal sites</u>
  - Not always productive
    - Reduced seed germination
    - Reduced plant growth
- <u>Egyptians</u>



(BEGLINGER AND LOCKE, 1957)

Biochar

- Is biochar "stable" in soil?

Biochar: Soil Stability ?

- Over a 100 year history of research
  - Potter (1908) – Initial observation of fungi/microbial degradation of lignite

Biochar Degradation Study	Residence Time (yr)
Steinbeiss et al. (2009)	<30
Hamer et al. (2004)	40 to 100
Bird et al. (1999)	50-100
Lehmann et al. (2006)	100's
Baldock and Smernik (2002)	100-500
Hammes et al. (2008)	200-600
Cheng et al. (2008)	1000
Harden et al. (2000)	1000-2000
Middelburg et al. (1999)	10,000 to 20,000
Swift (2001)	1,000-10,000
Zimmerman (2010)	100's to >10,000
Forbes et al. (2006)	Millennia based on C-dating
Liang et al. (2008)	100's to millennia

Possible Stability Explanation→ O:C Ratio

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Cheng et al. (2008)	1000
Forbes et al. (2006)	Millennia based on C-dating
Hamer et al. (2004)	40 (charred straw residue) 80 (charred wood)
Hammes et al. (2008)	200-600
Harden et al. (2000)	1000-2000
Liang et al. (2008)	several centuries to millennia
Lehmann et al. (2006)	100's
Middelburg et al. (1999)	10,000 to 20,000
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Swift (2001)	1,000-10,000
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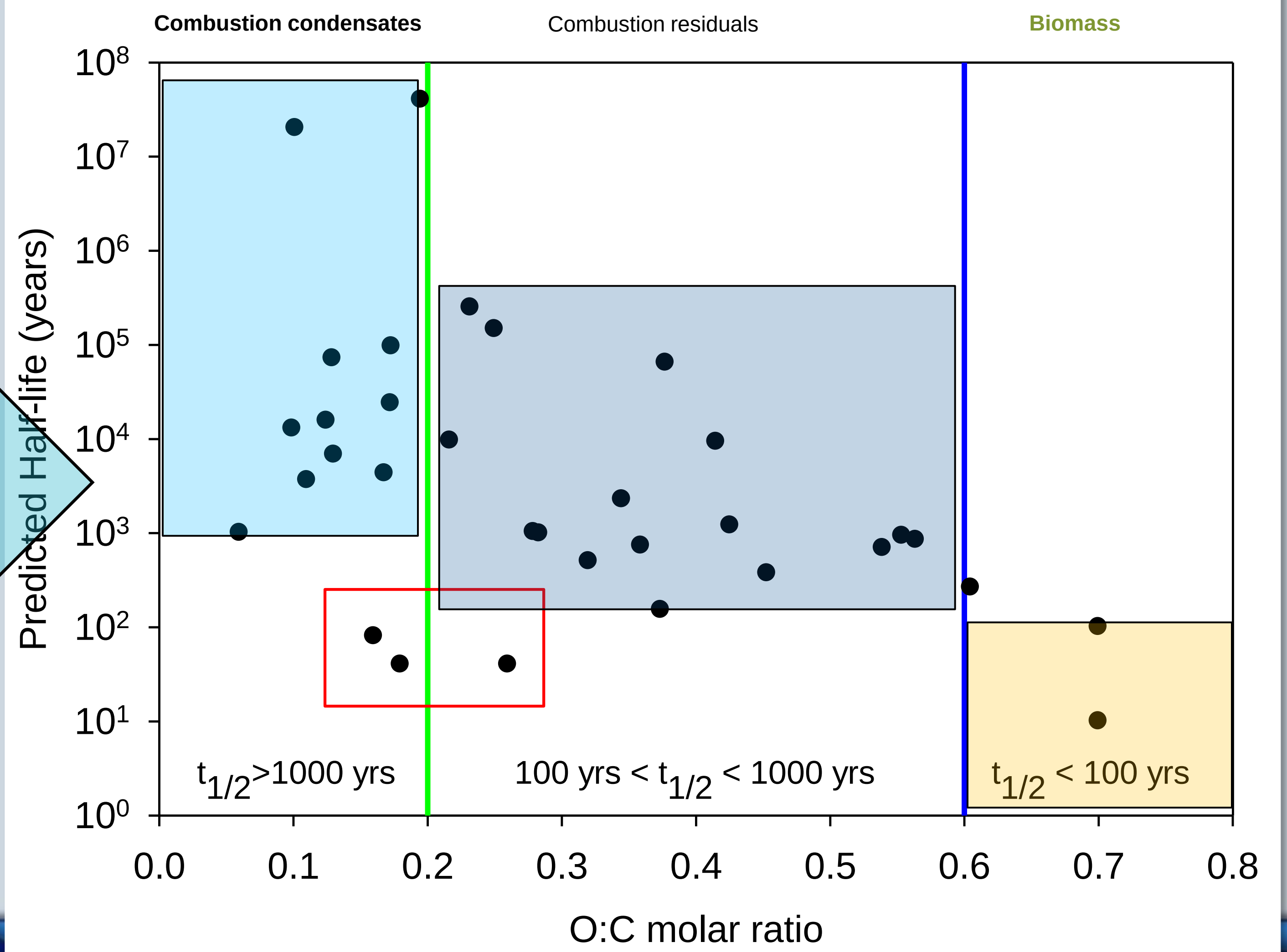


Summary of existing literature studies (n=35) on half-life estimation of biochar [Figure from Spokas (2010)]

Biochar

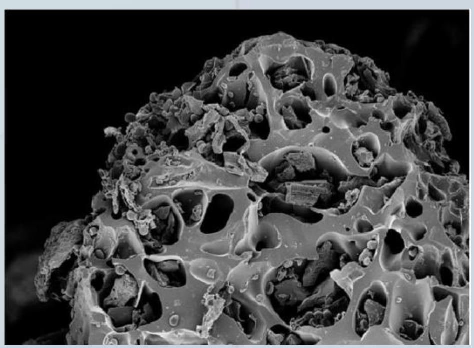
- Does biochar increase crop productivity?

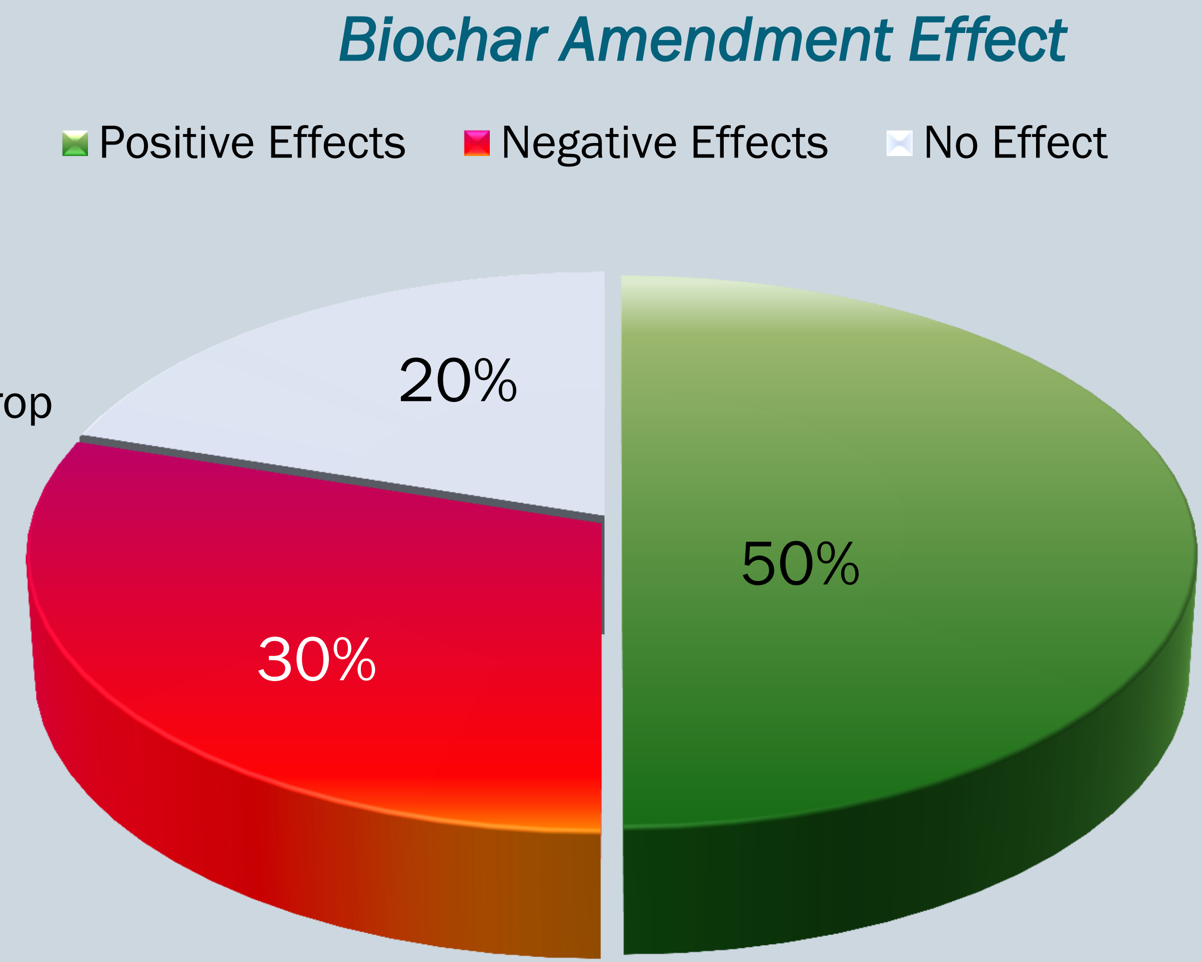
Biochar *Control*

Picture from → http://biocharfarms.org/about_biochar/

•Effect of Biochar Additions on Crop Growth/Yield

Summary of the existing studies and the corresponding effect on crop yield and/or growth from 1800's to current





For additional details see Spokas et al. (2012)

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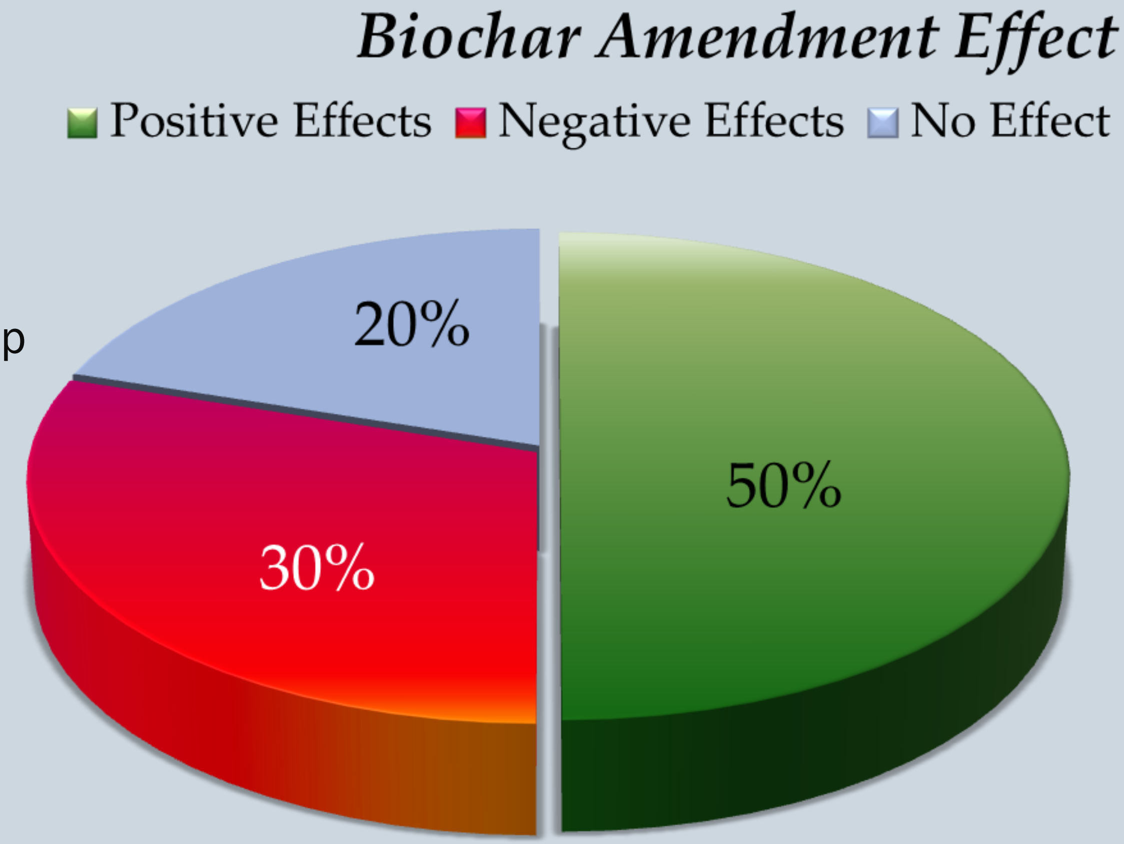
Summary of the existing studies and the corresponding effect on crop yield and/or growth from 1800’s to current



However, <u>should not</u> be used as a basis for forecasting outcomes → Publication bias

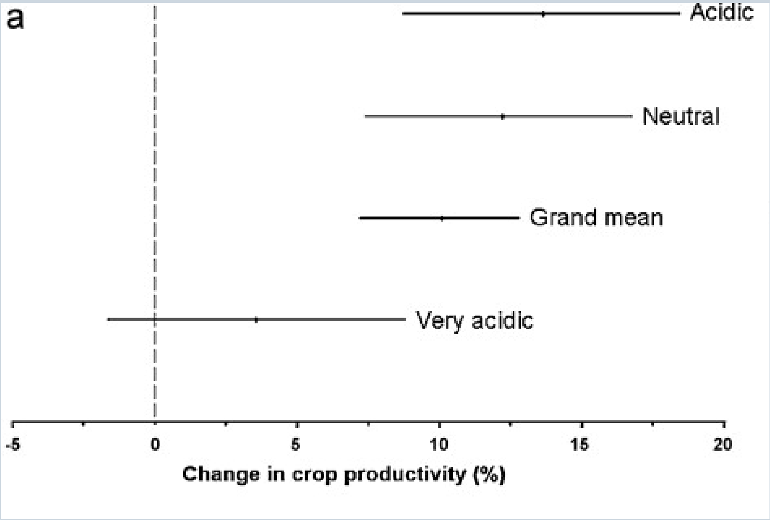
(Møller and Jennions, 2001)

•**Plant Growth Improvements**

•Recent meta-analyses reveal that biochar has the higher yield improvements in:

- Acidic & neutral pH soils (13-14%)
- Coarse or medium texture (10-13%)

Jeffery et al. (2011)



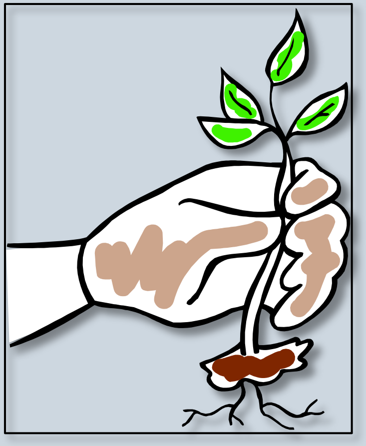
•Plant Growth Impacts

•*History:*

- *-- Wood based biochar yields the most consistent positive impacts*

•Numerous mechanisms:

- Addition of trace metals (Mo, B, S, Cu)
- pH alterations
- Sorbed compounds:
- Plant/germination/microbial inhibitory compounds
- Plant/microbial stimulants
- Aeration improvements/bulk density changes
- Soil moisture holding capacity improvements
- Microbial alterations following additions
- Increased nutrient holding capacity
- Root structure effects



• **Historic Issues**

Economic of applying charcoal on large scale.

- ***"On stiff clay soils it will produce an increase of vegetation, but not sufficient to pay the expense of the manure (charcoal)."***

Maryland State Agricultural Society (1822) p. 410

•**Historic Issues**

Economic of applying charcoal on large scale.

"On stiff clay soils it will produce an increase of vegetation, but not sufficient to pay the expense of the manure (charcoal)."

Maryland State Agricultural Society (1822) p. 410

"cost in many situations is probably too great to admit its profitable use as an ordinary manure."

The Cultivator (1849): "Improvement of the Soil" p. 342

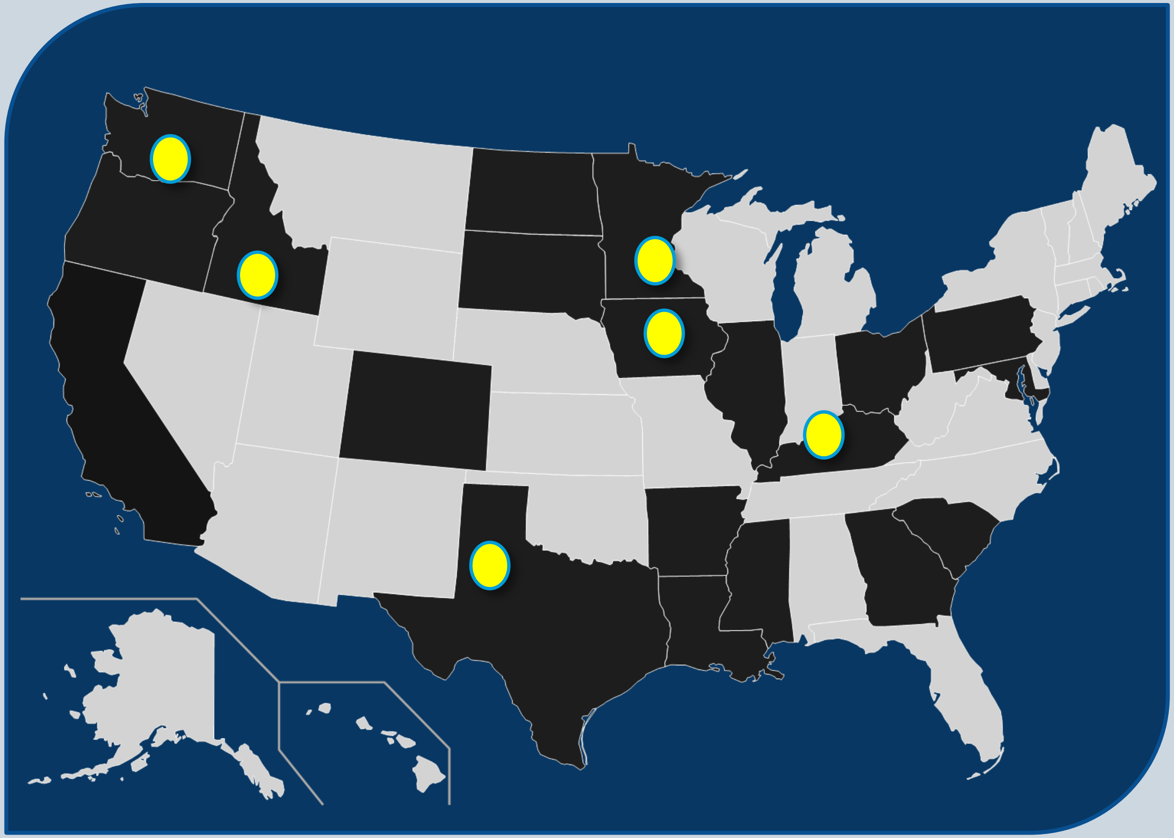
"Peat charcoal alone does not appear to be of value as a manure commensurate with its cost, and it will be necessary to reduce the cost of the manufacture of this article very considerably, before any extensive applications of it.."

Durden, E.H. (1849)

BIOCHAR RESEARCH

“I have but one lamp by which my feet are guided, and that is the lamp of experience.” - Patrick Henry.

USDA-ARS Biochar and Pyrolysis Initiative (CHARNet)

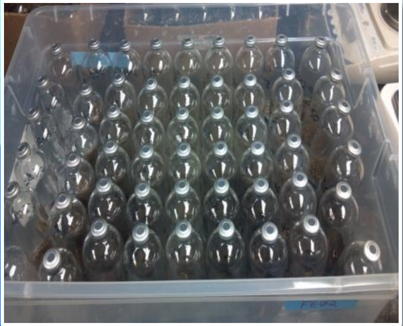


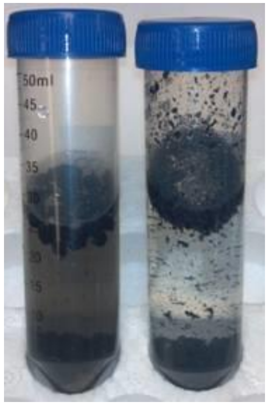
- Over 20 Locations – 6 Coordinated field plot locations

USDA

Agricultural Research Service

•St. Paul, MN Biochar Research





- **Field Plots – Rosemount, MN**
  - Soil C, Crop Yield, GHG flux
  - Biochar Weathering Effects

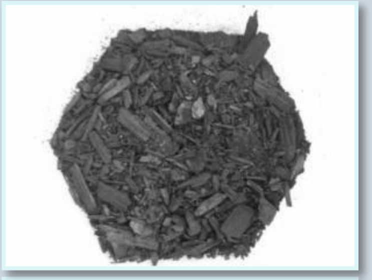
- **Laboratory/Greenhouse Studies**
  - Greenhouse Gas Impacts (N_2O, CH_4)
  - Nitrate/ammonia sorption
  - Nitrification/Denitrification inhibitor
  - Sorbed Organic Compounds
    - **PAH content : Specialty Crop Uptake/Bioaccumulation**
  - Developing optimized NO_3/PO_4 sorptive media

Research on Biochar Impacts on Soil Microbes & N Cycling

- 150+ different biochars evaluated
- Over 30 different biomass parent materials
  - Hardwood, softwood, corn stover, corn cob, macadamia nut, peanut shell, sawdust, algae, coconut shell, sugar cane bagasse, switchgrass, turkey manure, chicken feathers, distillers grain
- Represents a cross-sectional sampling of available "biochars"
  - C content 1 to 84 %
  - N content 0.1 to 2.7 %
  - Production Temperatures 350 to 850 ^{o}C

Variety of pyrolysis processes

- Fast, slow, hydrothermal, gasification, microwave assisted (MAP), & "entrepreneur" units




Corn (Stover,Cob,DG)

Pine

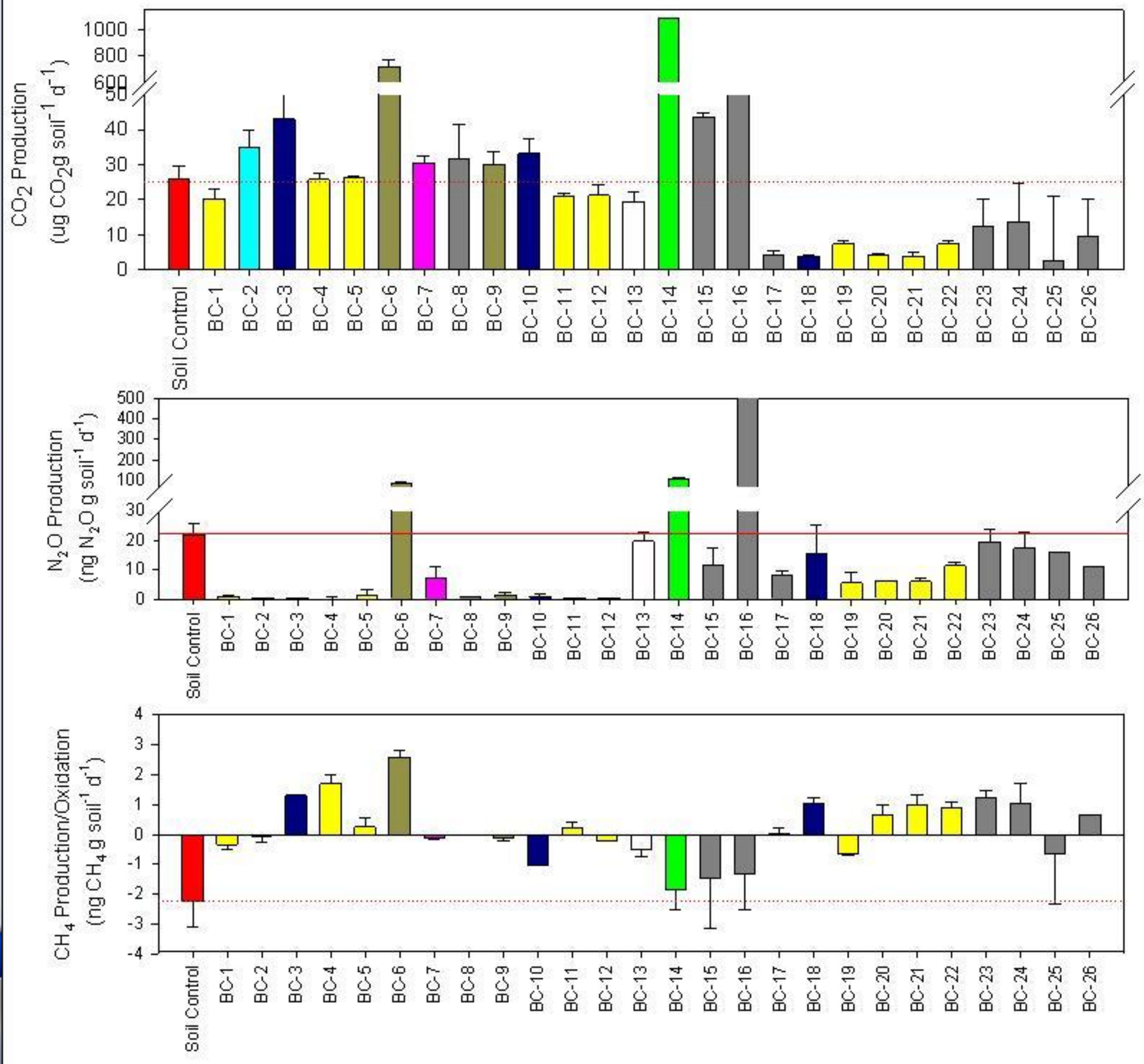
Shells: Peanut/mac)

Pine+Compost

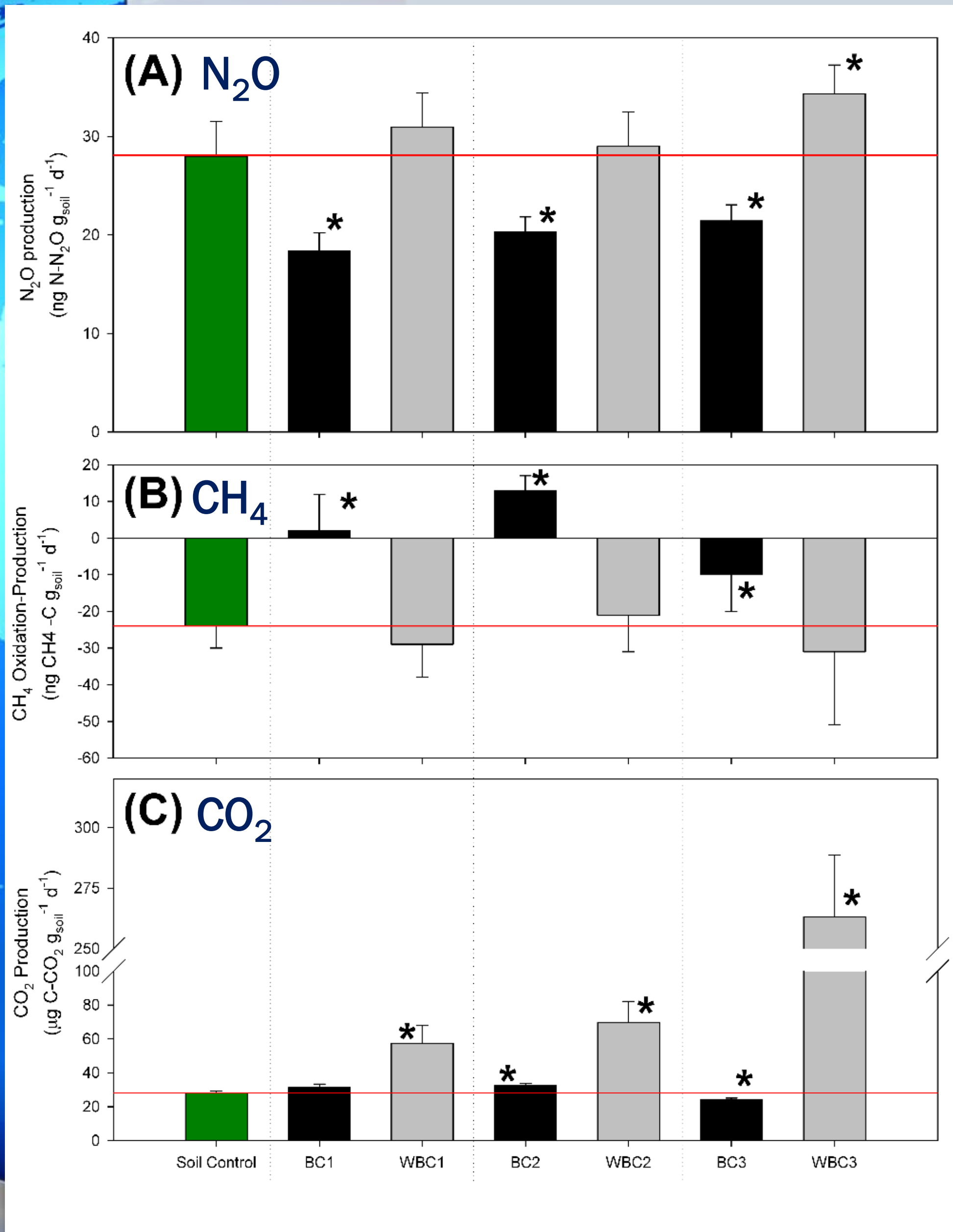
Turkey manure

Wood

Algae

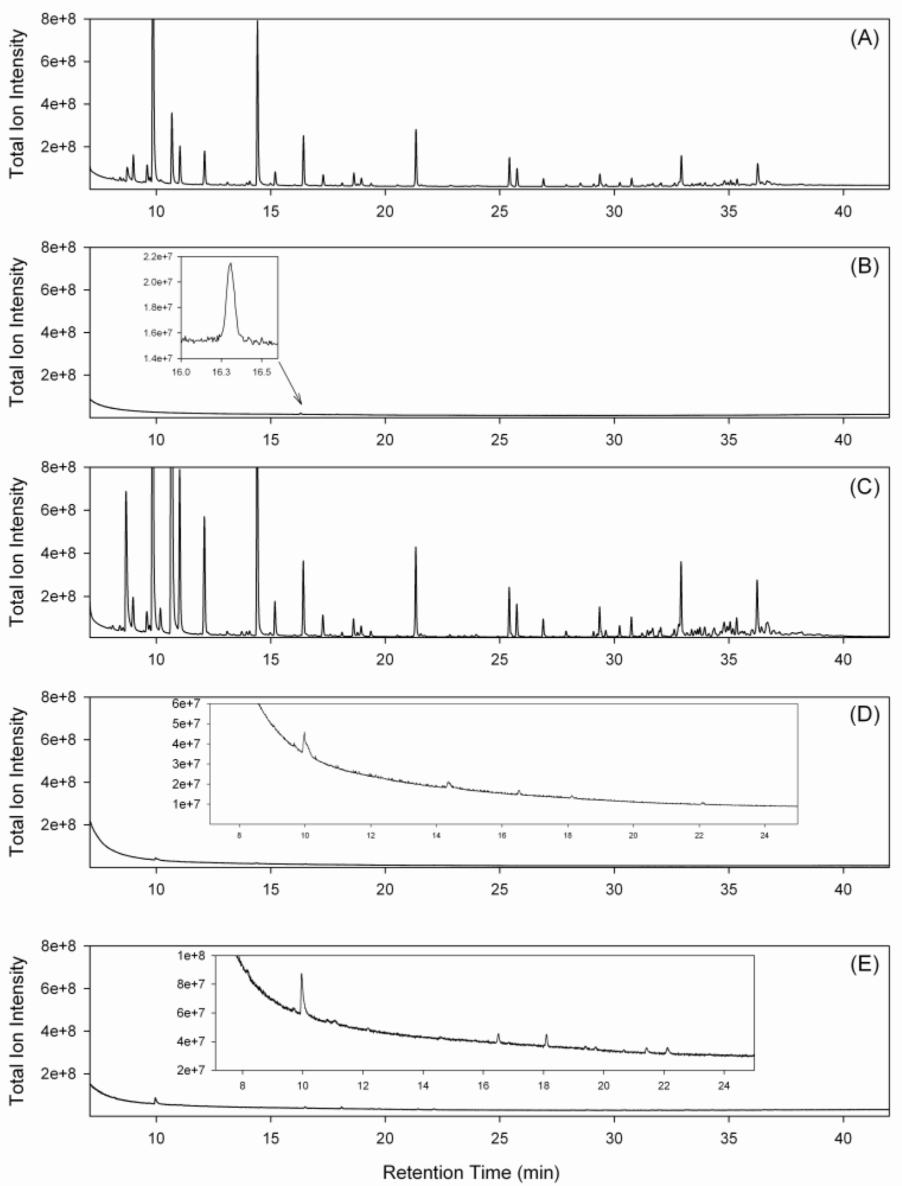


Weathering



- Weathering alters soil GHG responses
- Loss of N_2O mitigation
- Stimulation of CO_2 production (assumed from the weathered biochar)

Different Organic Species Sorbed to Biochars



Slow pyrolysis

Slow pyrolysis

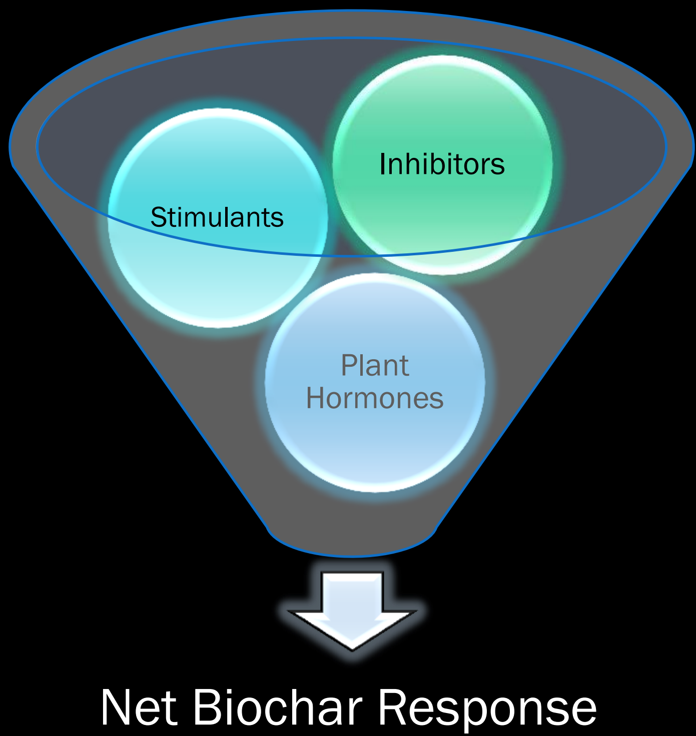
Equivalent production conditions

Fast pyrolysis

Gasifier pyrolysis

Soil kiln mound (traditional)

Impacts of Volatiles on Biochar

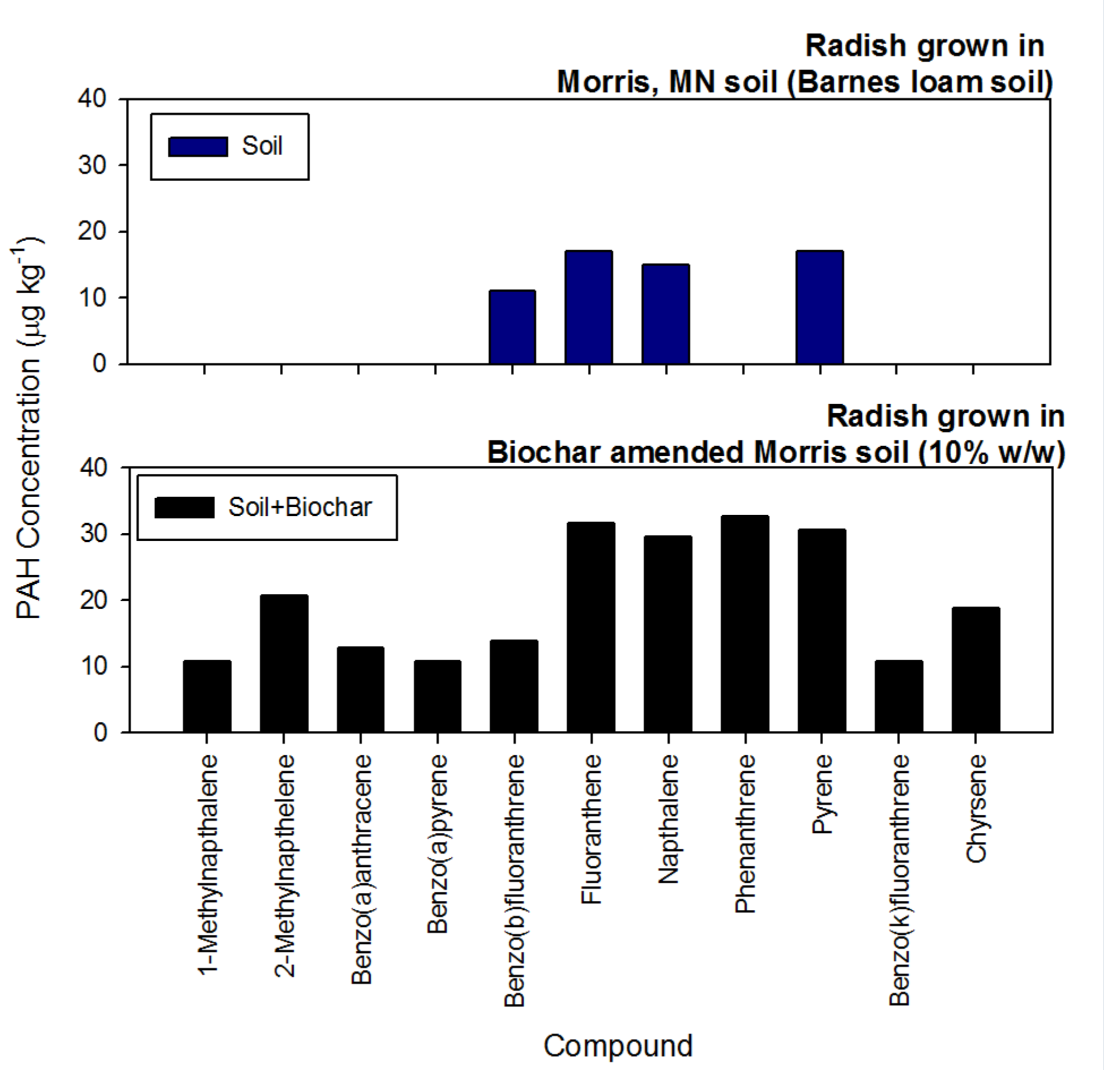


- **Nitrification Inhibitors**
  - Terpenoids [Amaral et al., 1998; White 1994]
  - Pyridines
  - Furfural (Couallier et al., 2006; Datta et al. 2001)
- **Other microbial inhibitors**
  - Benzene, esters
- **Interfere with microbial signaling** (communication)
  - Release or sorb signaling compounds
- **Alterations in VOC content could be sensitive indicators of soil conditions** (Leff and Fierer, 2008)
- **Still ongoing and developing research area in the plant/microbe research area**
  - *“Soil Volatilomics”* *(Insam and Seewald, 2010)*

PAH Biochar Content

- PAH content on biochar
  - Highly variable
- Range: Total USEPA-16 PAH content
  0.05 to 37 ppm (mg/kg)
- Appears to be mostly dependent on pyrolysis conditions
  - Oxygen presence
  - Water content of feedstock
- Higher PAH feedstock appears to lead to higher PAH biochar (e.g. sewage sludge)

PAH Bioaccumulation

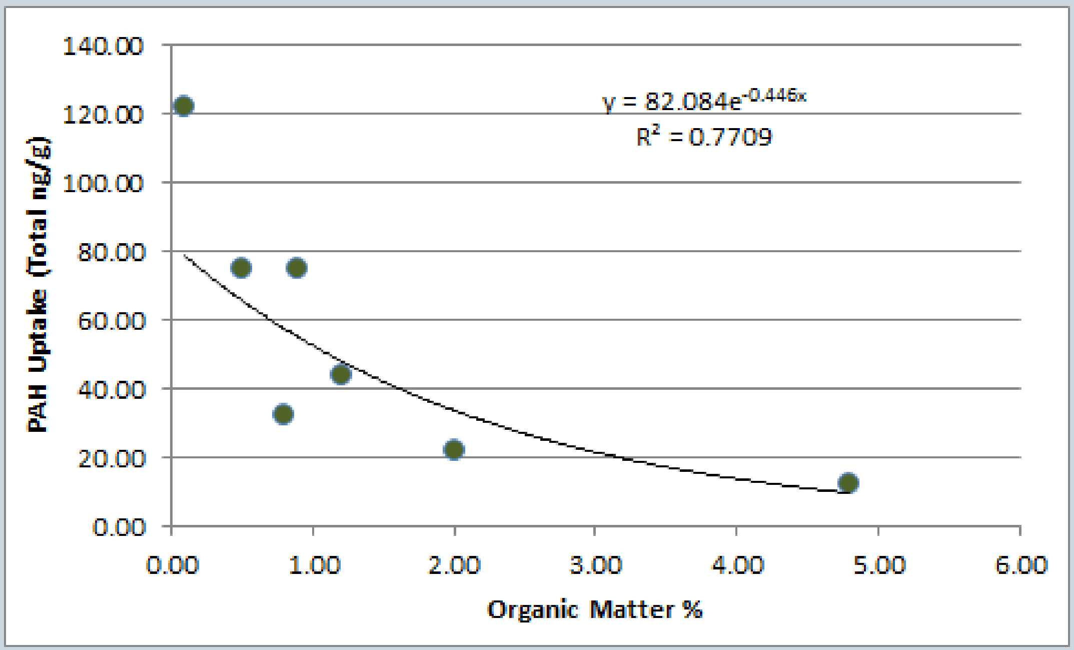


- Dependent on PAH content of biochar
- Original soil organic matter content
- Plant Species

PAH Uptake linked to soil organic matter

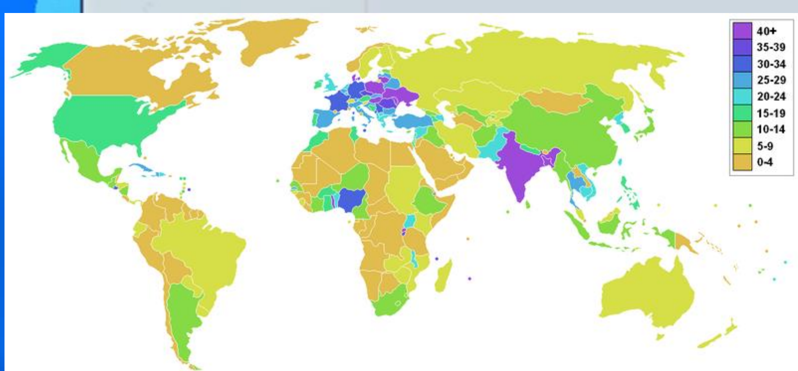
Largest controlling factor :
Soil organic matter

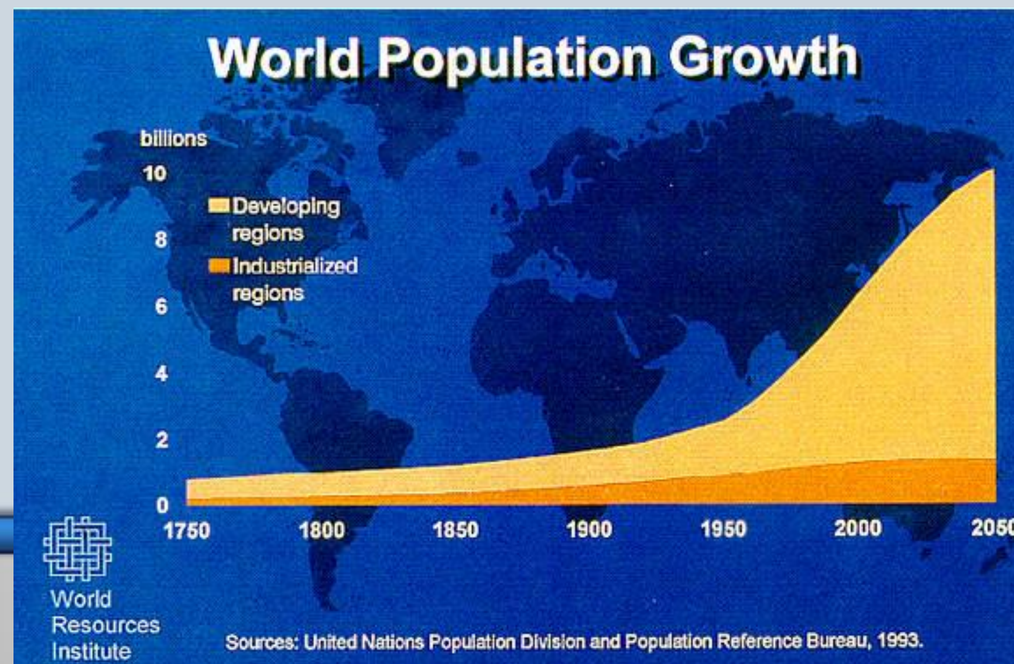
- Same biochar (21 mg/kg total PAH) mixed with different soils (10% w/w)



What about the future ??

- Several things have changed since the 1850's economics:
  - Global food pressure
    - Sufficient arable land ?
    - What price would be paid to "recover" unproductive land?





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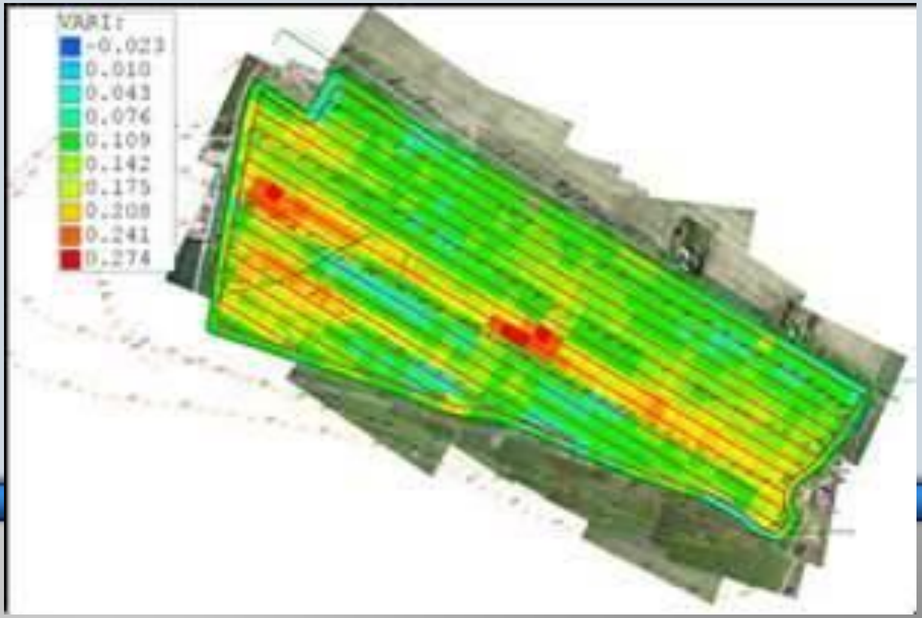
  - <u>Precision Farming</u> = Precision application



What about the future ??

- Several things have changed since the 1850's economics:
  - <u>Global food pressure</u>
  - <u>Precision Farming</u> = Precision application

  - With improved understanding

    = <u>Predictable results</u>

Conclusions

- Biochars are complex heterogeneous materials on all levels
  - Surface chemistries
  - Diverse microbial populations on biochar
  - Responses to nitrate/ammonium sorption
  - Implications on GHG emissions
  - Surface chemistries change with time (weathering)

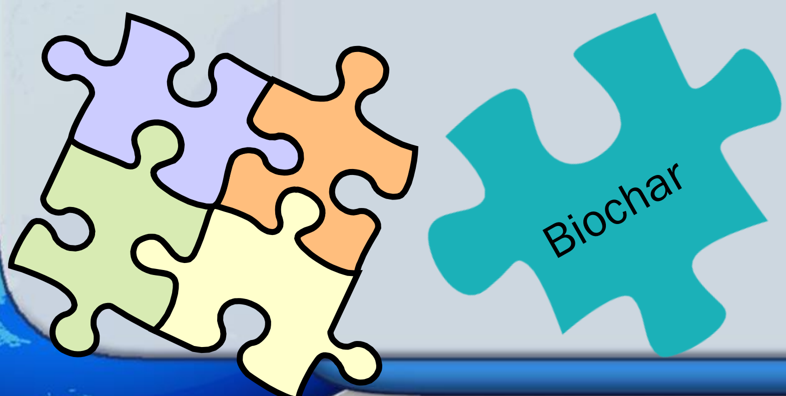
Conclusions

- Biochar can be a piece of the climate solution

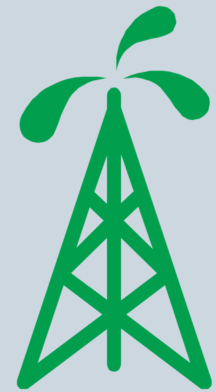
Just as the climate issues did not arise from a single source;

the solution to the problem will not be a <u>single solution.</u>

Soil C sequestration can be one piece of the solution, but multiple avenues should be utilized



- We are at a point where the pendulum is swinging away from fossil fuels and back to biomass as our source of energy

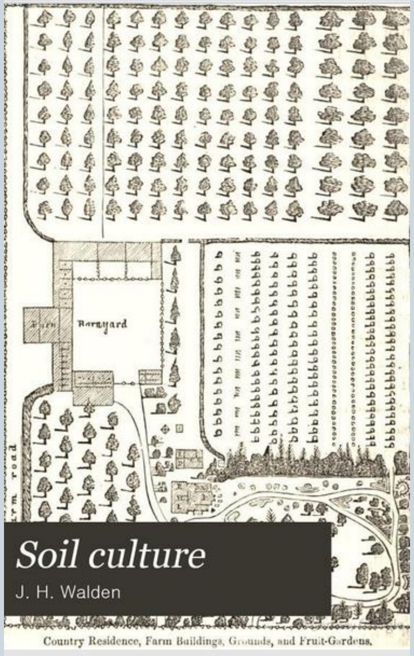


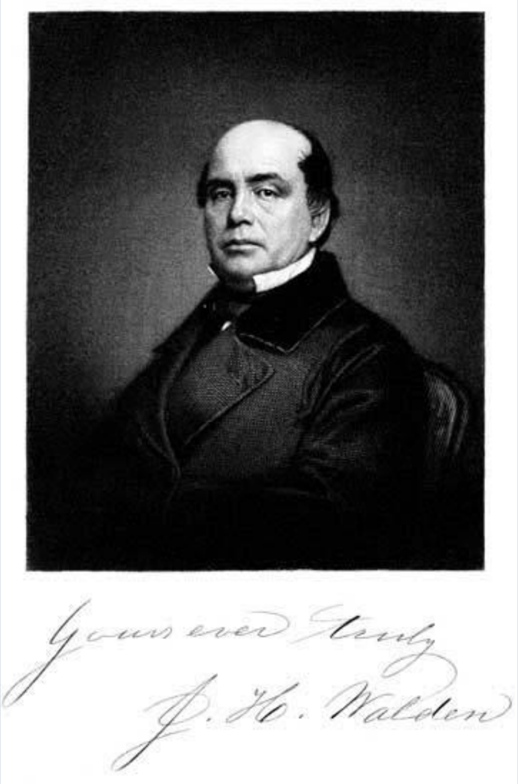
- We are at a point where the pendulum is swinging away from fossil fuels and back to biomass as the source of energy.
- We need to understand biochar's mechanisms to fully utilize the chemical, physical, and microbial properties of biochar to obtain the anticipated function.

  In other words, to optimize for a particular use or "designer biochar"(Novak, 2009)

"There are but few who realize the value of charcoal applied to the soil."

-J.H. Waldon (1860)





Minnesota Department of Agriculture – Specialty Block Grant Program

Minnesota Corn Growers Association

- Dynamotive Energy Systems
  - Fast pyrloysis char (CQuest™) through non-funded CRADA agreement
- Best Energies
  - Slow pyrolysis char through a non-funded CRADA agreement
- Northern Tilth
- Minnesota Biomass Exchange
- NC Farm Center for Innovation and Sustainability
- National Council for Air and Stream Improvement (NCASI)
- Illinois Sustainable Technology Center (ISTC) [Univ. of Illinois]
- Biochar Brokers
- Chip Energy
- AECOM
- Penn State
- University of Bonn (Germany)
- Laboratorio di Scienze Ambientali R.Sartori - C.I.R.S.A. (University of Bologna, Italy)
- IRNAS-CSIC (Spain)
- USDA-ARS Biochar and Pyrolysis Initiative

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